

Laboratory Testing of Bridge Deck Mixes

Project Description

Early crack development has been noticed in many of MoDOT's bridge decks. The cracks have been attributed to high thermal or shrinkage stress development at early ages in the concrete. These cracks accelerate concrete deterioration and corrosion of reinforcing steel that shorten the service lives and increases the maintenance costs of bridge decks.

This study was conducted to develop a new bridge deck mix design that has low cracking potential, low permeability, good durability, and adequate strength. The mix designs developed in this study will improve field performance and minimize cracking potential compared to MoDOT's current (B-2) bridge deck mix design.

Laboratory-testing on 11 different PCC bridge deck mix designs were conducted. Each test mix differed by the type and/or the amount of supplementary cementitious material that replaced Type 1 Portland cement. The different mix designs are described in Table 1. The supplementary cementitious materials used in this study included Class C flyash, ground granulated blast furnace slag (GGBFS), silica fume, and ternary combinations of these materials.

Table 1 - Mix Descriptions

Mix No.	Cementitious Materials
1	Control, 728 lb/yd ³ , No Water Reducer
2	Control, 728 lb/yd ³ - 15% Flyash, No Water Reducer
3	602 lb/yd ³ , Type A Water Reducer
4	602 lb/yd ³ - 15% Flyash, Type A Water Reducer
5	602 lb/yd ³ - (35% Flyash), Type A Water Reducer
6	602 lb/yd ³ - (25% Slag), Type A Water Reducer
7	602 lb/yd ³ - (50% Slag), Type A Water Reducer
8	602 lb/yd ³ - (6% Silica Fume), Type A Water Reducer
9	602 lb/yd ³ - (15% Flyash & 25% Slag), Type A Water Reducer
10	602 lb/yd ³ - (15% Flyash & 6% Silica Fume) Type A Water Reducer
11	602 lb/yd ³ - (25% Slag & 6% Silica Fume), Type A Water Reducer

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The following tests were conducted to evaluate and compare the concrete characteristics for each mix design:

Fresh Concrete Characteristics

- Slump (AASHTO T119)
- Percent Air Content (AASHTO T152)
- Unit Weight (AASHTO T121)
- Water/Cement Ratio
- Finishing Observations

Cracking Potential

- Plastic Shrinkage Test in Slabs
 - Research Test
- Cracking Tendency of Concrete Ring
 - Research Test
- Autoclave Expansion (ASTM C151)
- Dry Shrinkage of Mortar Bars (ASTM C596)

Permeability

- Rapid Chloride Permeability (AASHTO T277)
- 90-Day Ponding Test (AASHTO T259)

Durability

- Freeze/Thaw Durability (AASHTO T161)
- Salt Scaling Resistance (ASTM C672)

Strength Properties

- 3, 7, 14, 28, 56, and 90 day compressive strength (AASHTO T22)
- Heat of hydration (ASTM C1074)
- 3, 7, 14, 28, and 56 day modulus of elasticity (ASTM C469)

Laboratory Results

Fresh Concrete Characteristics

Emphasis was placed to make each mix design equal in workability using the slump test and the percent air content as guides. The target slump was 3 ½ inches and the target air content was 6%. The water/cement ratio was measured at these target values. Fresh concrete characteristics are listed in Table 2.

Cracking Potential

Laboratory tests that determine the cracking potential of a concrete mix designs were conducted, however all test results from the *plastic shrinkage test of slabs*, *cracking tendency of concrete rings*, *autoclave expansion*, and *dry shrinkage of mortar bars*, were inconclusive in evaluating and comparing the cracking tendencies of the different mix designs.

Permeability

Two permeability tests were conducted to determine the concrete's resistance to chloride ion penetration. The 90-day ponding results showed favorable results for all mix designs tested, but failed to compare the different

Table 2 - Fresh Concrete Characteristics

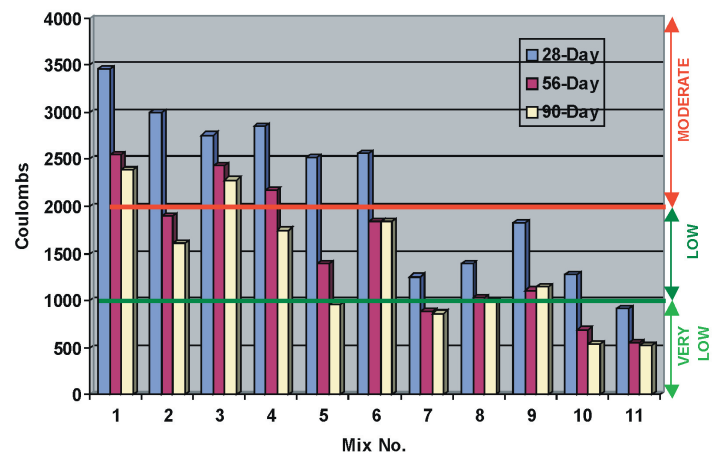
Mix No.	Mix Description	Cementitious Content (sacks/yd ³)	Avg. w/c ratio	Avg. Slump (in)	Avg. Air (%)
1	Control	7.74	.389	3.50	6.3
2	Control (15% Flyash)	7.74	.369	3.63	6.2
3	No Supp. Cementitious Mtls.	6.40	.412	3.40	6.4
4	15% Flyash	6.40	.390	3.25	6.0
5	35% Flyash	6.40	.370	3.20	5.9
6	25% GGBFS	6.40	.412	3.15	6.1
7	50% GGBFS	6.40	.420	3.70	5.6
8	6% Silica Fume (SF)	6.40	.428	4.05	6.0
9	15% Flyash, 25% GGBFS	6.40	.398	4.13	6.4
10	15% Flyash, 6% SF	6.40	.420	3.55	5.8
11	25% GGBFS, 6% SF	6.40	.442	3.85	5.8

mix designs. The rapid chloride permeability (RCP) test effectively evaluated the eleven mix designs.

Figure 1 illustrates the RCP results for each mix design. Mixes that did not contain supplementary cementitious materials (Mix 1 and Mix 3) yielded over 2000 Coulombs, which is considered moderate permeability. Class C flyash or GGBFS replacement in a concrete mix (Mix 4 and Mix 6) yielded low permeability at 90 days. Increasing the replacement dosage of flyash and GGBFS (Mix 5 and Mix 7) further decreased the permeability into the low and very low ranges for the 28, 56, and 90-day tests. Mix 9 contained a ternary combination of 15% Class C flyash and 25% GGBFS that yielded low permeability.

Mix 8, which contained 6% silica fume, yielded very low permeability. Adding flyash or GGBFS with the silica fume, Mixes 10 and 11 (both ternary mixes), also yielded very low permeability of less than 1000 Coulombs. The main benefit of silica fume is that it provides a dense, low permeable mix

Figure 1 - Permeability Results



Durability

Resistance to freezing/thawing conditions and salt scale resistance were the tests conducted to evaluate the durability of the 11 mix designs. A good quality aggregate was used in this study so that the freeze/thaw resistance of the different types and amounts of cementitious materials could be determined. Freeze/thaw results indicated that all mixes obtained a durability factor greater than 90, which is considered excellent durability.

The resistance to salt scaling was observed and rated for each mix design. Salt scale resistance is determined based upon a visual scale ranging from 0 (No Scaling) to 5 (Severe Scaling). The addition of any supplementary cementitious materials (Class C flyash, GGBFS, and/or silica fume) appeared to slightly decrease the salt scale resistance of the concrete, but the effect was not considered significant. The salt scale ratings of mixes containing supplementary cementitious materials (Mixes 4-11) typically rated at a 1 rating (slight scaling) or a 2 rating (slight to moderate scaling).

Increased dosage amounts of Class C flyash and GGBFS (Mix 5 and 7, respectively) did not continue to decrease the salt scale resistance. Also, ternary combinations of cementitious materials (Mix 9, 10, and 11) performed equal or better compared to the single supplementary cementitious mixes.

ASTM C672 is considered to be harsh laboratory test in evaluating a concrete mix's salt scale resistance. A laboratory salt scale rating of 2 or less is considered acceptable for bridge deck applications in Missouri. Field ratings will be conducted on future projects to ensure that salt scaling is not an issue with supplementary cementitious materials.

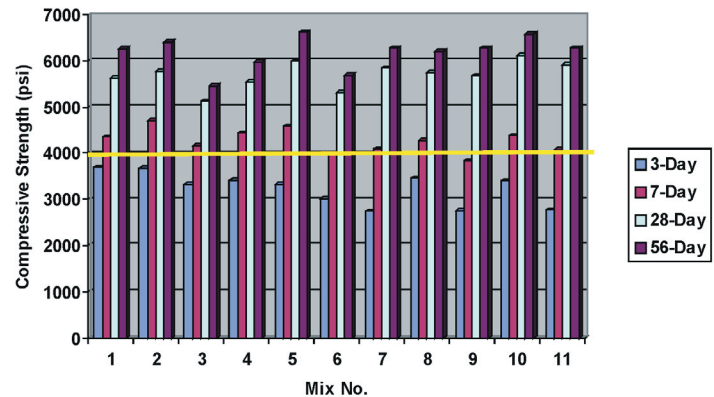
Compressive Strength

Compressive strength data were collected from 3, 7, 14, 28, 56, and 90 day concrete test cylinders that represented each laboratory mix design. Figure 2 graphically illustrates the 3, 7, 28, and 56-day compressive strengths of each mix design. MoDOT has a minimum 28-day design compressive strength requirement of 4000 psi for its bridge decks. All mix designs achieved this requirement within seven days. All mix designs achieved over 5000 psi at 28 days, which is considered more than adequate strength for bridge decks. Lower compressive strengths, especially low early strengths, are generally more desirable for bridge decks because of the lower heat of hydration generated and lower early cracking potential.

When supplementary cementitious materials and a Type A water reducer were used in a mix containing a reduced cement content 6.40 sacks/yd³ (Mixes 4–11), the compressive strengths were equivalent or higher than the B-2 control mixes. GGBFS has a lower heat of hydration than

Portland cement and will generally retard the setting time of concrete. The laboratory results likewise indicated that test mixes 6, 7, 9, and 11 that contained ground granulated blast furnace slag (GGBFS) yielded a lower 3 and 7-day compressive strengths compared to all other mixes as illustrated in Figure 2. After 7-days, the compressive strengths of the GGBFS mixes compared similar to the B-2 control mixes.

Figure 2 - Compressive Strength Results



Heat of Hydration

Lowering the heat of hydration of a concrete mix is one of many recommendations to reduce thermal stresses and mitigate early bridge deck cracking. Peak hydration temperatures were measured on 4"x 8" specimens for each of the mix designs. Reducing the cement content from 7.74 sk/yd³ to 6.40 sk/yd³ reduced the heat generated. Mixes containing Class C flyash and GGBFS yielded even lower peak temperatures. Silica fume mixes (Mixes 8-11) had higher peak temperatures than the flyash and GGBFS mixes but was lower compared to the B-2 mix (Mix 1) containing 7.74 sk/yd³ of Portland cement.

Modulus of Elasticity

The modulus of elasticity affects both thermal and shrinkage stresses more than any other physical concrete property. Increasing the concrete modulus of elasticity increases both shrinkage and thermal stresses. Modulus of elasticity testing was performed on 3, 7, 14, 28, and 56-day cylinders that were fabricated to represent each of the 11 different mix designs.

The results indicated that mixes containing GGBFS (Mix 6, 7, and 9) had lower early 3-day modulus of elasticity (Approx. 3.6 million psi.) compared to the other mix designs (4.0 – 5.6 million psi.). The benefits of using GGBFS are that it provides concrete with a low early strength and low early modulus to reduce thermal and shrinkage stresses in concrete, therefore reducing the potential for early cracking in bridge decks.

Mix 8 (6% silica fume replacement) provided a higher early 3-day modulus (5.6 million psi) and therefore more sensitive to early cracking. Using silica fume in combination with flyash or GGBFS decreased the early 3-day modulus of elasticity to 4.0 million psi.

Cost Analysis

The cost of the 11 different mix designs were estimated and compared to determine the most cost effective mix design. The eleven mix designs differed mostly by type and amounts of cementitious material and the addition of a Type A water reducer. The prices of cementitious materials may vary considerably and depend on project location, project size, and available shipping means. Table 3 provides a cost comparison of only the cementitious materials and the water reducing admixtures. All other common ingredients were taken out of the estimate, assuming that the costs are comparable.

According to the cost estimate reducing the minimum total cementitious materials from 7.50 sk/yd³ to 6.40 sk/yd³, replacing Portland cement with Class C flyash and GGBFS, and the addition of a Type A water reducer will provide MoDOT with a savings of approximately \$6.00/yd³. The use of silica fume would increase the cost of MoDOT's bridge decks by approximately \$8.00/yd³.

Table 3 - Cost Estimate

Mix No.	Total Cost (\$/yd ³)
1	30.21
2	26.92
3	27.18
4	24.44
5	20.75
6	25.46
7	23.72
8	40.09
9	22.71
10	37.34
11	38.36

Key Findings

The main findings of this investigation can be summarized as follows:

- All mixes tested in this study achieved acceptable compressive strength and excellent freeze/thaw durability factors.
- Reducing Portland cement content to 6.40 sk/yd³ achieved more than adequate strength for Missouri's bridge decks.
- Replacing Portland cement with a supplementary cementitious material in the 6.40 sk/yd³ mixes yielded compressive strengths equivalent to or greater than the control mixes.
- Mixes containing 25% and 50% GGBFS yielded lower early strengths and lower early modulus of elasticity compared to other mixes. Concrete with lower early strength and lower early concrete modulus have less thermal and shrinkage stresses that cause early bridge deck cracking.

- Decreasing total cementitious content and the use of supplementary cementitious materials slightly decreased the salt scale resistance of concrete. However, these results and the results from all mixes tested were found acceptable for bridge deck applications in Missouri.
- The use of flyash, GGBFS, and/or silica fume significantly decreased concrete's permeability. Concrete mixes without a pozzolan or cementitious admixture yielded moderate permeability, which is too high to be acceptable for bridge deck applications in Missouri.

Recommendations

Based on the laboratory results from this study, Research, Development, and Technology makes the following recommendations:

- The minimum total cementitious material in bridge deck mixes should be reduced from 7.50 sk/yd³ to 6.40 sk/yd³ to reduce the drying shrinkage potential and thermal stresses that induce cracking in bridge decks.
- The addition of a Type A water reducer should be used in bridge deck mixes to ensure strength, permeability, and workability requirements.

At least one of the following supplementary cementitious materials should be incorporated into bridge deck mixes at the recommended replacement limits.

Supplementary Cementitious Material	Maximum Limits
Max. Flyash Replacement	25 %
Max. GGBFS Replacement	40 %
Max. Total Portland Cement Replacement with Supplementary Cementitious Materials	40 %

- A ternary mix containing Type 1 Portland cement, 15% flyash, and 25% GGBFS (Mix 9) should be encouraged and used whenever possible because of its superior concrete properties, lower cost, and its desired compatibility compared to mixes containing Type 1 Portland and Class C flyash.
- Silica fume is not recommended based upon cost, workability issues, and its plastic shrinkage cracking potential.

Field documentation and verification should be conducted to verify the performance of the bridge deck mix designs proposed in this study.

For More Information

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